

Systematic uncertainties between different heavy quark models

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Shanshan Cao

Wayne State University



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Two directions of studying heavy quarks

- Understand heavy quark dynamics in a thermal medium – e.g. mass effect on parton energy loss
- Probe the QGP property with heavy quarks – e.g. quantify the heavy-quark-medium interaction with transport coefficients

Drag (diffusion) coefficient

$$A = -\frac{d\langle p_L \rangle}{dt} \quad \text{Average longitudinal momentum loss per unit time}$$

$$A_a = \sum_{b,(a'X)} \int d\sigma_{ab \rightarrow a'X} \rho_b (p_L^a - p_L^{a'})$$

$d\sigma_{ab \rightarrow a'X}$ HQ property and HQ-medium interaction ρ_b medium property

Spatial diffusion coefficient $D_s = \lim_{p \rightarrow 0} \frac{T_p}{MA(p)}$

Transverse transport coefficient

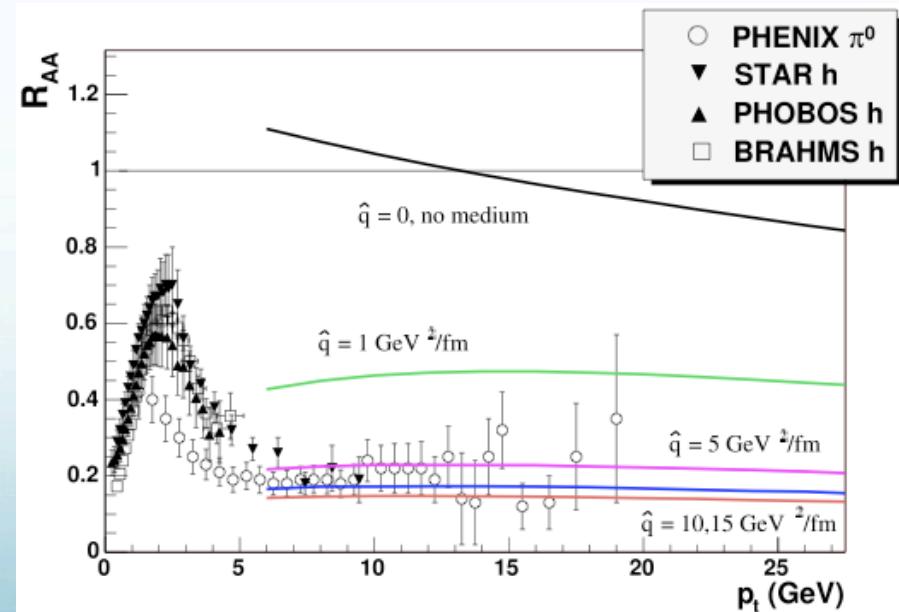
$$\hat{q} = \frac{d\langle k_{\perp}^2 \rangle}{dt}$$

Average transverse momentum broadening square per unit time due to elastic scatterings with medium

$$\hat{q}_a = \sum_{b,(cd)} \int_{\mu_D^2}^{s/4} dk_{\perp}^2 \frac{d\sigma_{ab \rightarrow cd}}{dk_{\perp}^2} \rho_b k_{\perp}^2$$

$\frac{d\sigma_{ab \rightarrow cd}}{dk_{\perp}^2}$ HQ property and HQ-medium interaction ρ_b medium property

- Crucial parameter input in many theory calculations of radiative energy loss

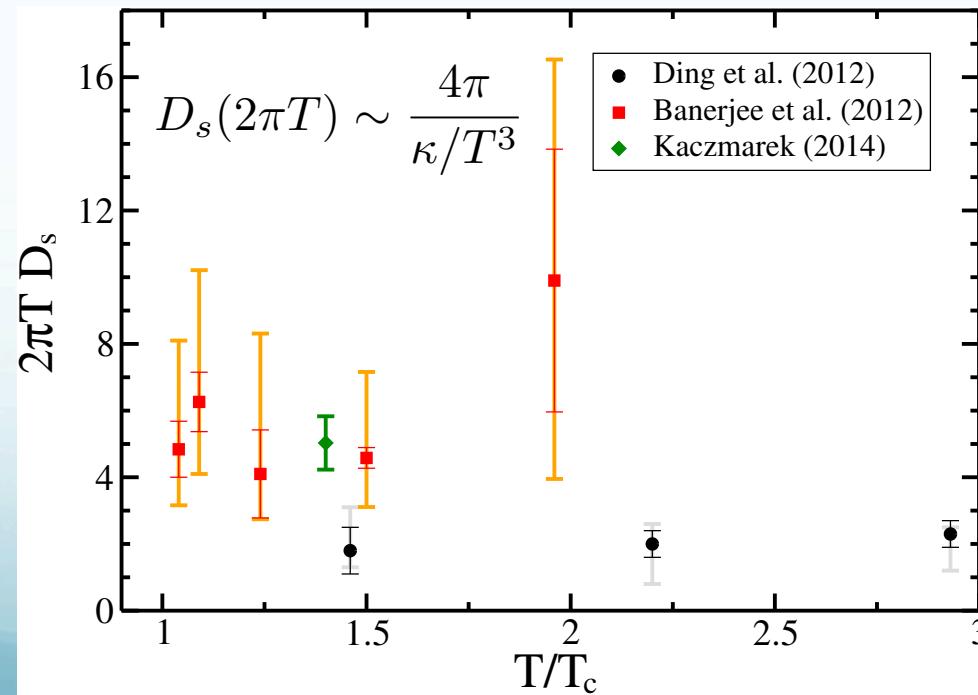


Lattice QCD calculation of D_s

- Calculate transport coefficient from the correlation function of conserved currents via the slope of spectral function ρ_E at $\omega = 0$

$$\kappa/T^3 = \lim_{\omega \rightarrow 0} 2T\rho_E(\omega)/\omega \quad (\text{Kubo formula})$$

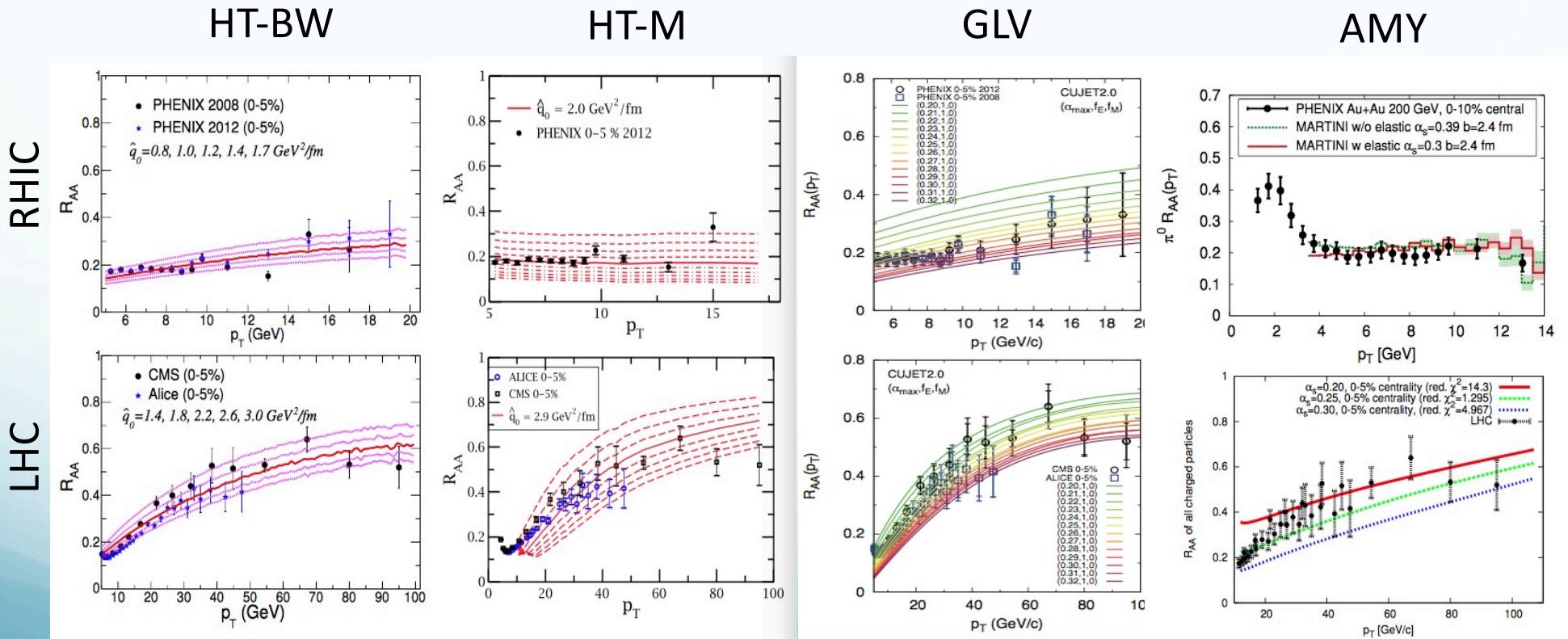
- Large error bars
- No results for finite momentum HQ yet



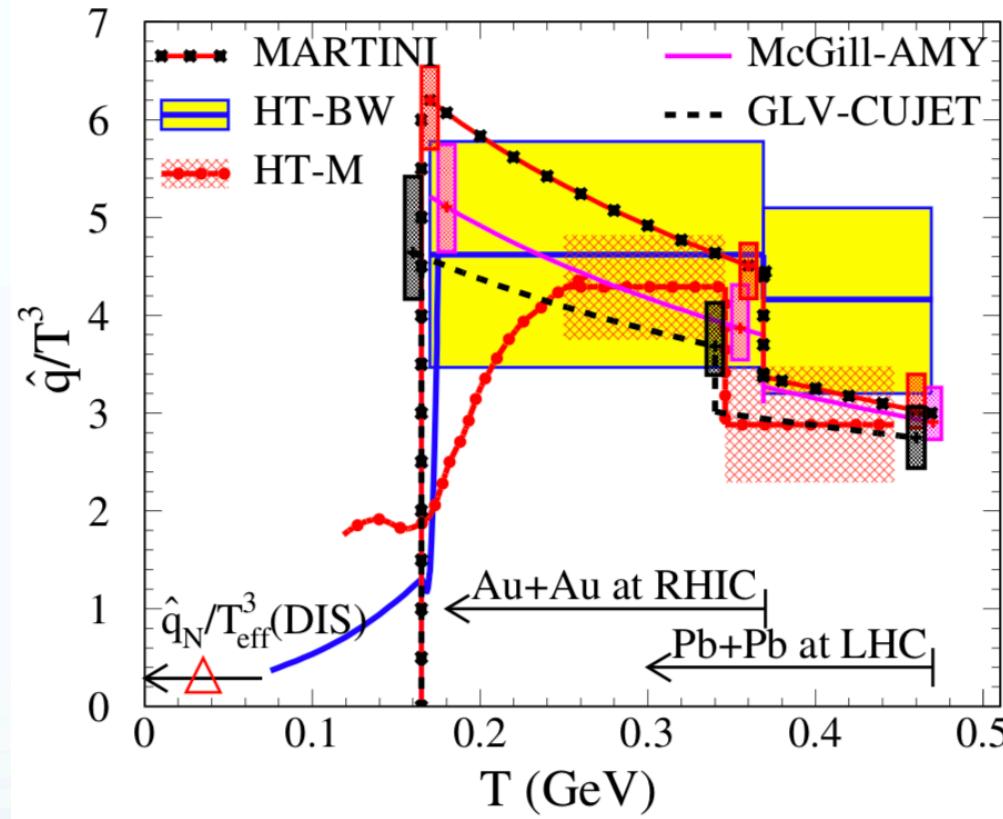
Extraction from model-to-data comparison

Example: jet qhat from JET Collaboration work

- Compare different energy loss formalisms to data within a common hydro medium [PRC 90 (2014) 014909]



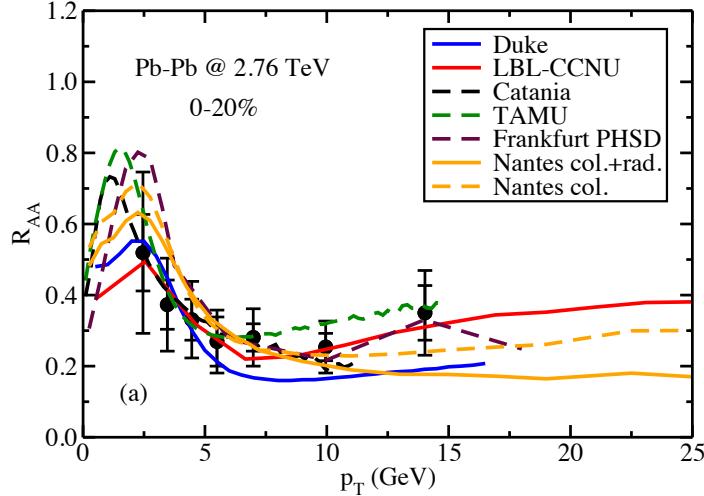
Extraction from model-to-data comparison



- Band – systematical uncertainty from different theory inputs (within a factor of 2)
- Can we constrain heavy quark models and the extracted transport coefficients as well?

Bad constraints on HQ coefficients

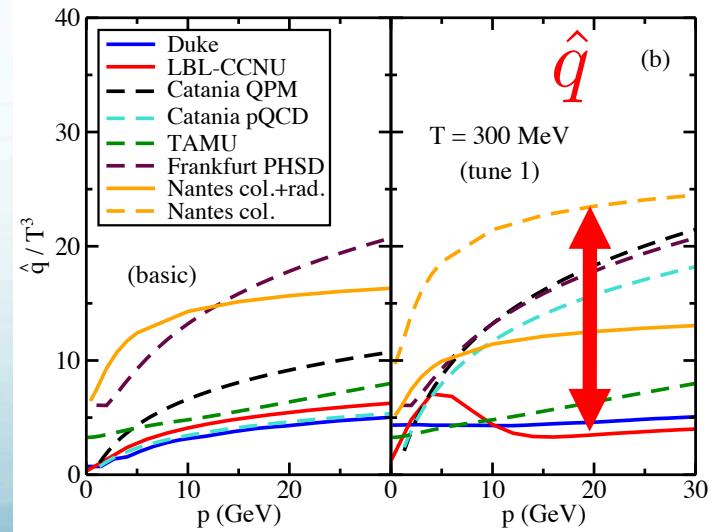
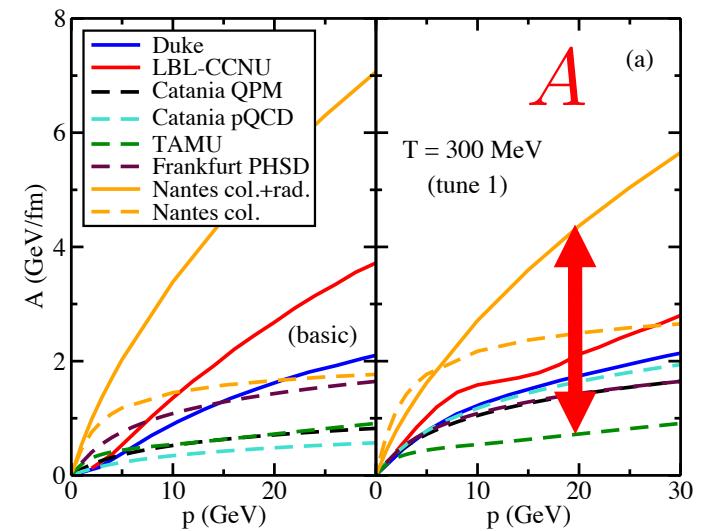
Reasonable description of data



Models	2.76 ATeV Pb-Pb	200 AGeV Au-Au
Duke	0.769	2.819
LBL-CCNU	0.132	1.49
Catania	0.113	1.01
TAMU	0.178	2.40
Frankfurt PHSD	0.637	1.59
Nantes col. + rad.	0.629	17.3
Nantes col. only	0.524	17.9

TABLE I. Values of $\chi^2/\text{d.o.f.}$ from model to data comparison.

Divergence in the extracted coefficients



Complexity of HQ dynamics

Jets

- High p_T , dominated by radiative energy loss
- Similarity between different formalisms (pQCD)
- Less sensitive to hadronization (fragmentation)
- Common hydro has been applied

Heavy quarks

- From low to high p_T , both collisional and radiative energy loss
- Diversity of model calculations (col. vs. rad.; pQCD vs. non-perturbative)
- Complicated hadronization process (fragmentation and coalescence)
- Common hydro has NOT been applied yet

Goal of this talk: discuss systematic uncertainties from different sources: energy loss, initial state, bulk, hadronization, etc.

S. Cao et. al., Phys. Rev. C99 (2019) 054907 [JET Collaboration]

R. Rapp et. al., Nucl. Phys. A979 (2018) 21-86 [EMMI-RRTF]

Y. Xu et. al., Phys. Rev. C99 (2019) 014902 [Duke-Frankfurt]

Systematic uncertainty in energy loss

S. Cao et. al., Phys. Rev. C99 (2019) 054907 [initiated by JET Collaboration]

Models	energy loss theory	transport model	elastic	inelastic
Duke	pQCD	Langevin	✓	✓
LBL-CCNU	pQCD	Boltzmann	✓	✓
Catania QPM	QPM	Boltzmann	✓	
Catania pQCD	pQCD	Langevin	✓	
TAMU	T -matrix	Langevin	✓	
Frankfurt PHSD	QPM	Boltzmann	✓	
Nantes col. + rad.	pQCD	Boltzmann	✓	✓
Nantes col. only	pQCD	Boltzmann	✓	

Toward the determination of heavy-quark transport coefficients in quark-gluon plasma

Shanshan Cao,¹ Gabriele Coci,^{2,3} Santosh Kumar Das,^{4,2} Weiyao Ke,⁵ Shuai Y. F. Liu,⁶ Salvatore Plumari,² Taesoo Song,⁷ Yingru Xu,⁵ Jörg Aichelin,⁸ Steffen Bass,⁵ Elena Bratkovskaya,^{9,10} Xin Dong,¹¹ Pol Bernard Gossiaux,⁸ Vincenzo Greco,^{2,3} Min He,¹² Marlene Nahrgang,⁸ Ralf Rapp,⁶ Francesco Scardina,^{2,3} and Xin-Nian Wang^{13,11,*}

¹Department of Physics and Astronomy, Wayne State University, Detroit, Michigan 48201, USA

²Department of Physics and Astronomy, University of Catania, Via Santa Sofia 64, I-95125 Catania, Italy

³Laboratori Nazionali del Sud, INFN-LNS, Via Santa Sofia 62, I-95123 Catania, Italy

⁴School of Physical Science, Indian Institute of Technology Goa, Ponda, Goa, India

⁵Department of Physics, Duke University, Durham, North Carolina 27708, USA

⁶Cyclotron Institute and Department of Physics and Astronomy, Texas A&M University, College Station, Texas 77843, USA

⁷Institut für Theoretische Physik, Universität Gießen, Germany

⁸SUBATECH, IMT Atlantique, Université de Nantes, CNRS-IN2P3, Nantes, France

⁹Institute for Theoretical Physics, Johann Wolfgang Goethe Universität, Frankfurt am Main, Germany

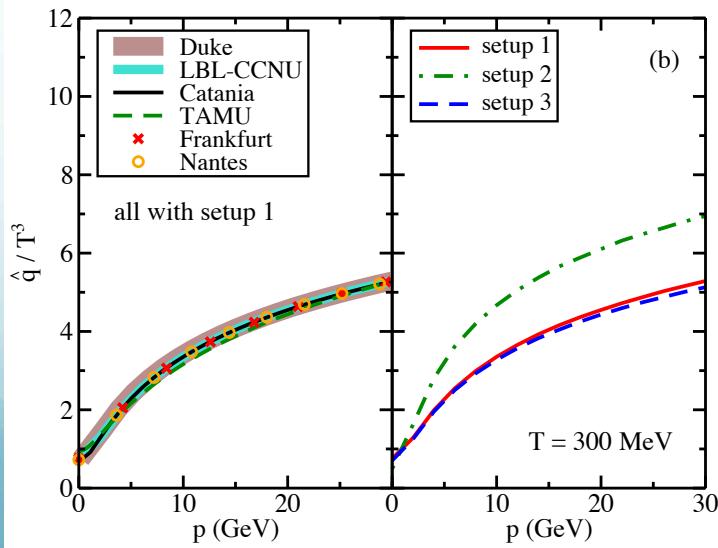
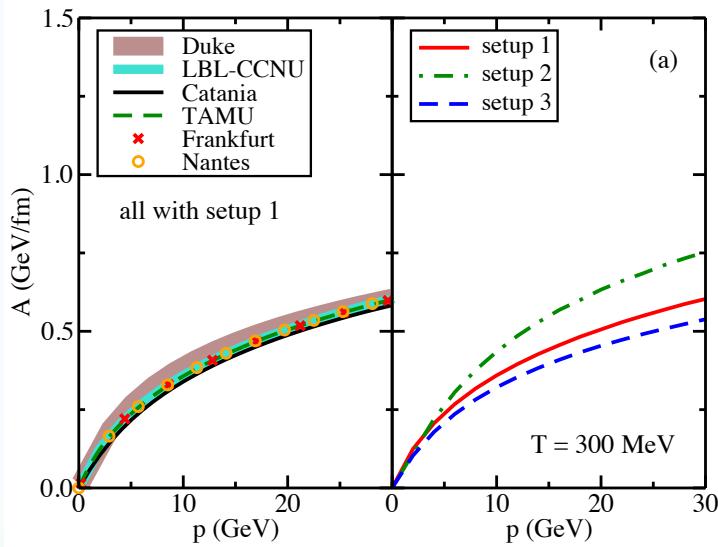
¹⁰GSI Helmholtzzentrum für Schwerionenforschung GmbH, Darmstadt, Germany

¹¹Nuclear Science Division, Lawrence Berkeley National Laboratory, Berkeley, California 94740, USA

¹²Department of Applied Physics, Nanjing University of Science and Technology, Nanjing 210094, China

¹³Key Laboratory of Quark and Lepton Physics (MOE) and Institute of Particle Physics, Central China Normal University, Wuhan 430079, China

Baseline check for evaluating coefficients



- The simplest 2->2 pQCD cross section with fixed $\alpha_s = 0.3$, massless light partons and $M_c = 1.5$ GeV
- All groups pass the baseline check
- Quantify possible uncertainties

Setup 1 vs. setup 2:

$$\frac{1}{t} \rightarrow \frac{1}{t - \mu_D^2} \quad \frac{1}{t} \rightarrow \frac{1}{t} \theta(-\mu_D^2 - t)$$

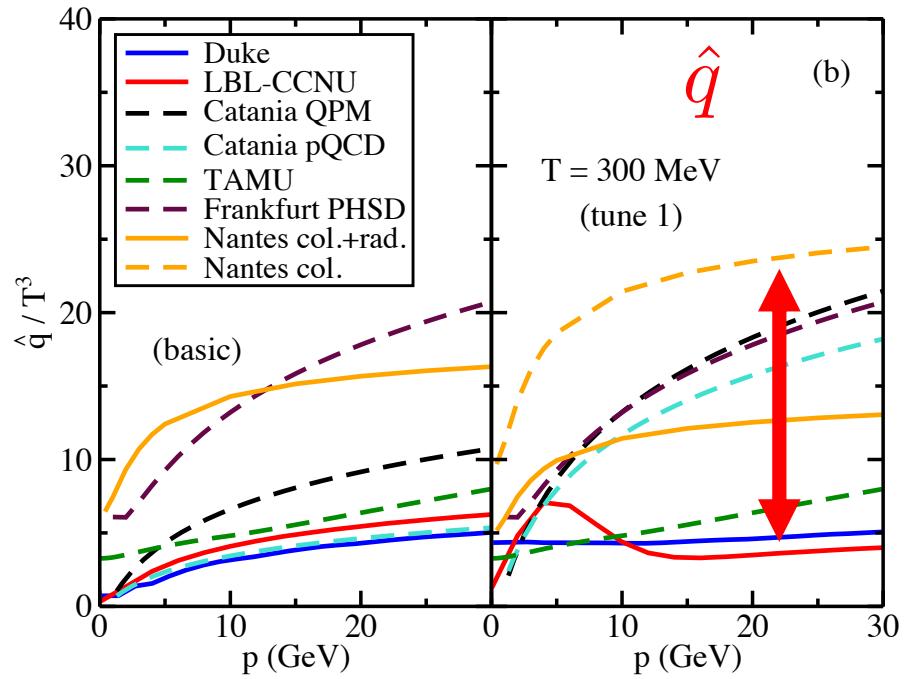
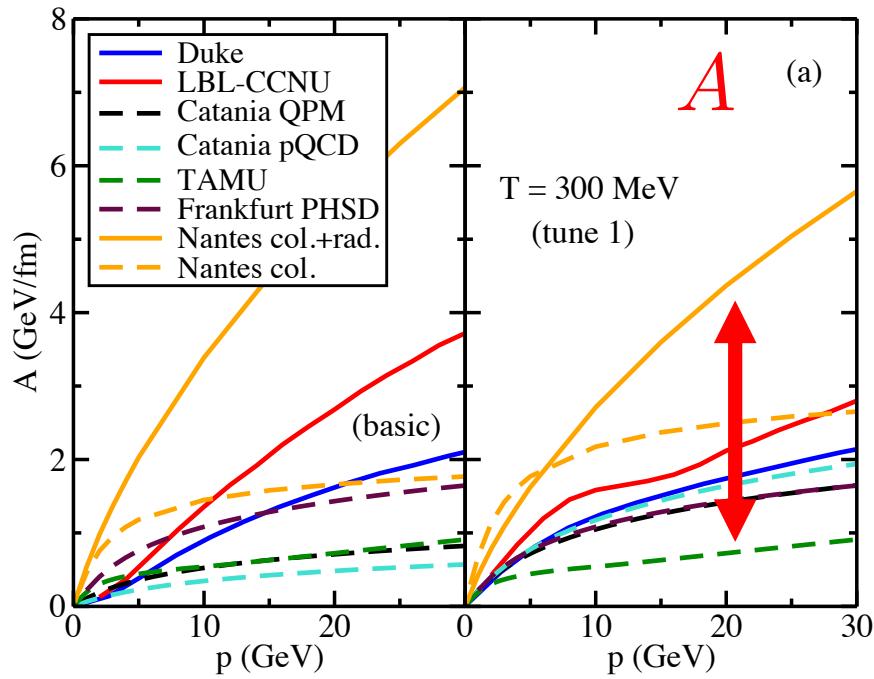
Setup 1 vs. setup 3:

Quantum vs. classical statistics for light parton distribution

HQ coefficients in different model setups

Basic: directly calculated coefficients in different HQ models

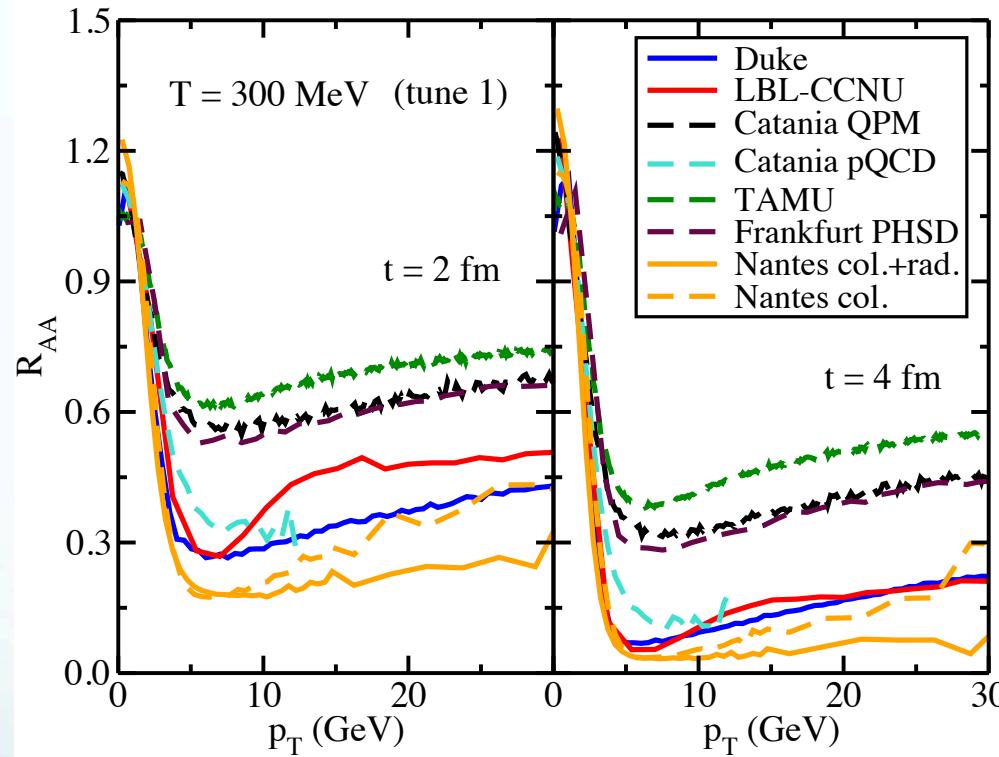
Tune 1: extracted coefficients after tuning model to the LHC data



- How much discrepancy is from HQ-medium interaction?
- How much discrepancy is from different assumptions of the medium and hadronization?

R_{AA} in a brick without hadronization

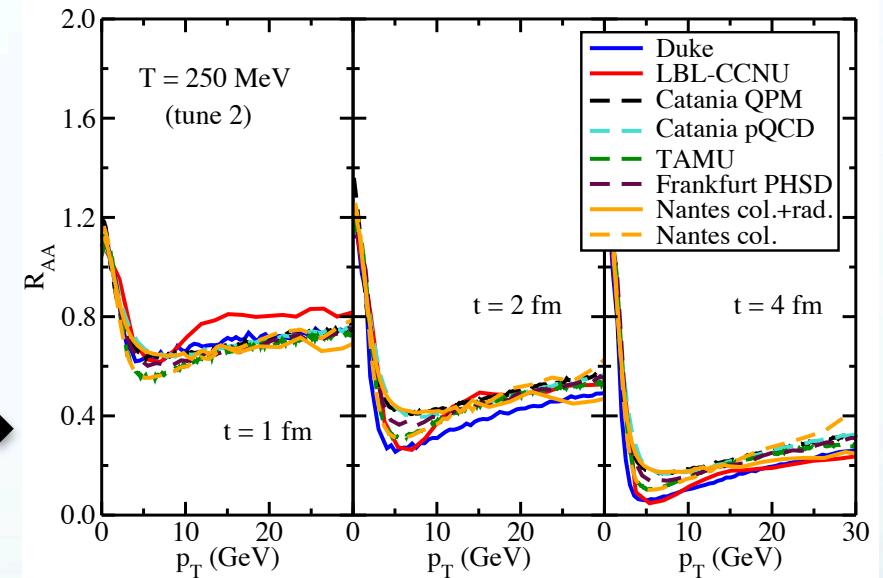
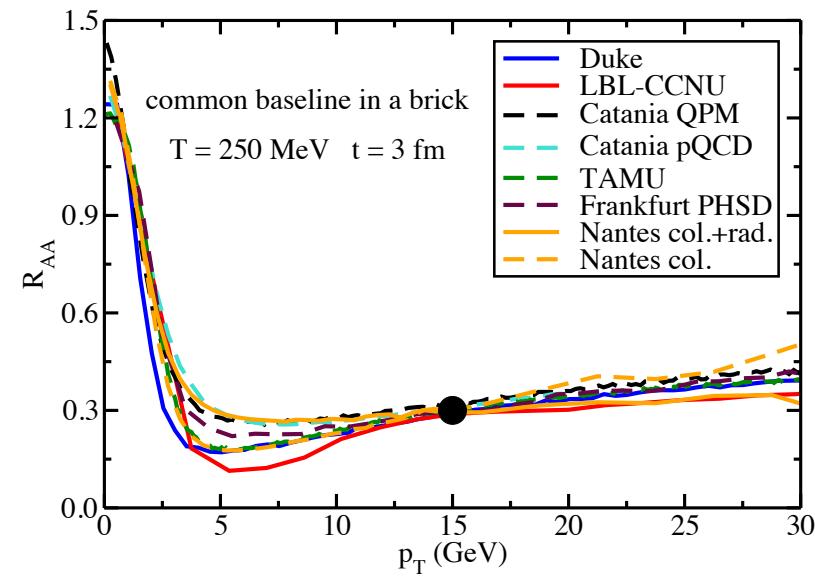
- Apply “tune 1” coefficients in a static medium
- No hadronization \rightarrow charm quark R_{AA}



- Very different charm R_{AA} in a brick
- Different medium and hadronization indeed brings significant uncertainties in the extracted HQ coefficients

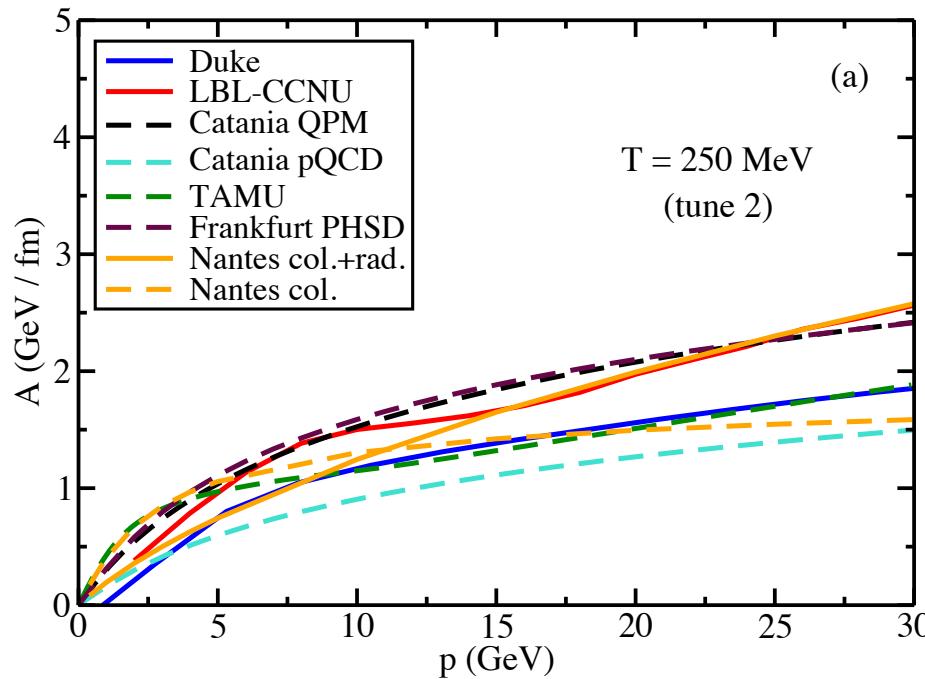
Systematic error ONLY due to energy loss

Common baseline: same initial c spectrum, static medium $T = 250$ MeV, $L = 3$ fm, $R_{AA}(c) = 0.3$ at $p_T = 15$ GeV

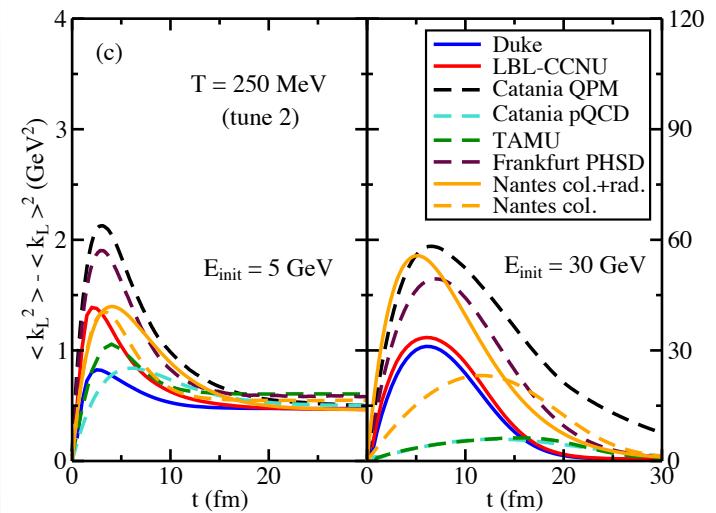


- Eliminate uncertainties from the medium and hadronization
- Reasonable convergence of R_{AA} at other evolution times
- Differences in path length dependence of energy loss still exist

Drag coefficient from the common baseline

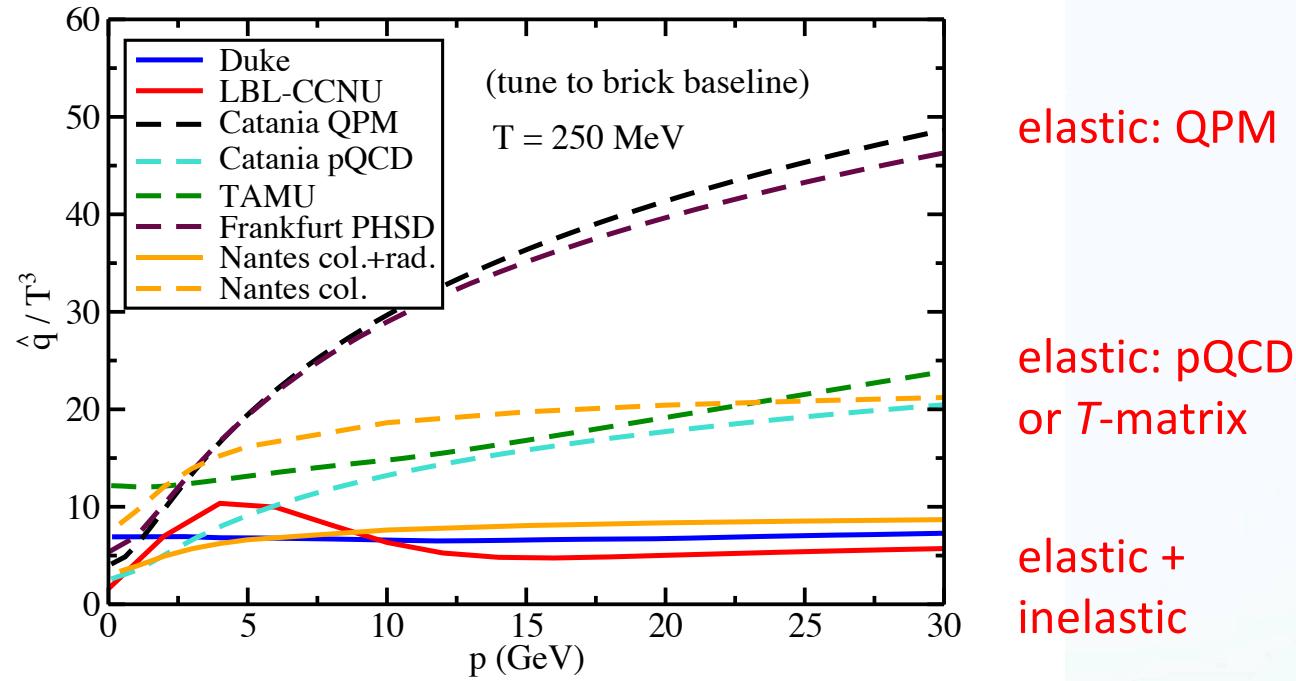


Longitudinal momentum fluctuation vs. time



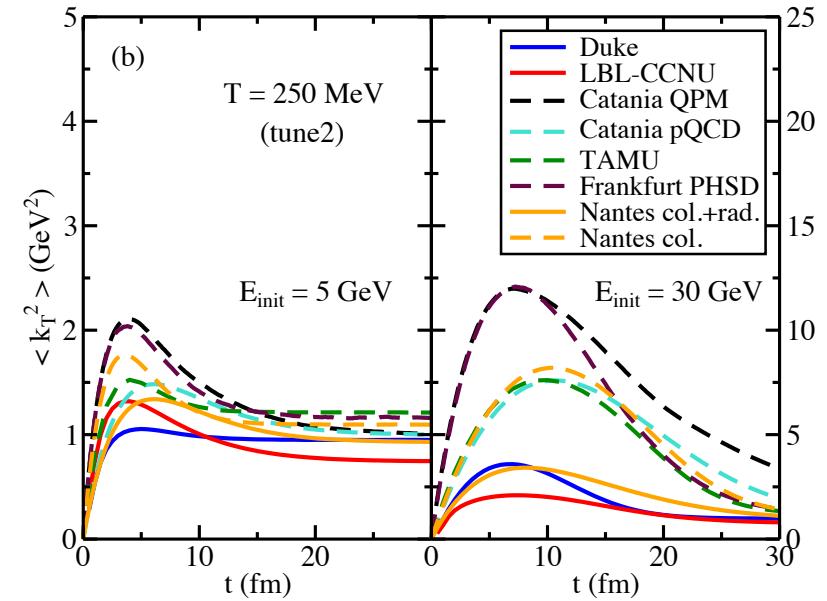
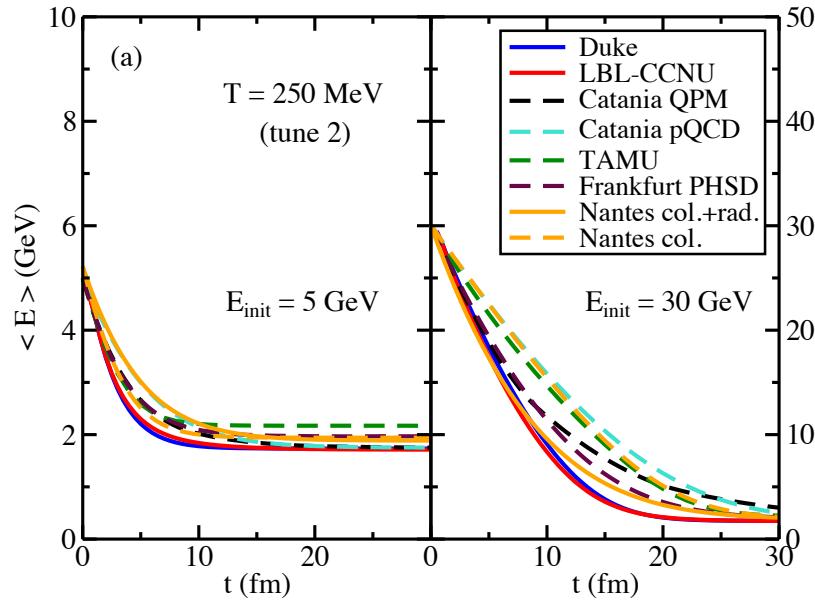
- Convergence of the drag coefficient within a factor of 2
- Drag coefficient quantifies the mean HQ energy loss
- Remaining uncertainties: different energy loss fluctuations in different models

Transverse transport coefficient



- Convergence of transport parameter into 3 groups: elastic + inelastic, elastic only (pQCD or T -matrix), elastic only (QPM with larger thermal mass and Debye screening mass)
- Similar energy loss, different transverse momentum broadening

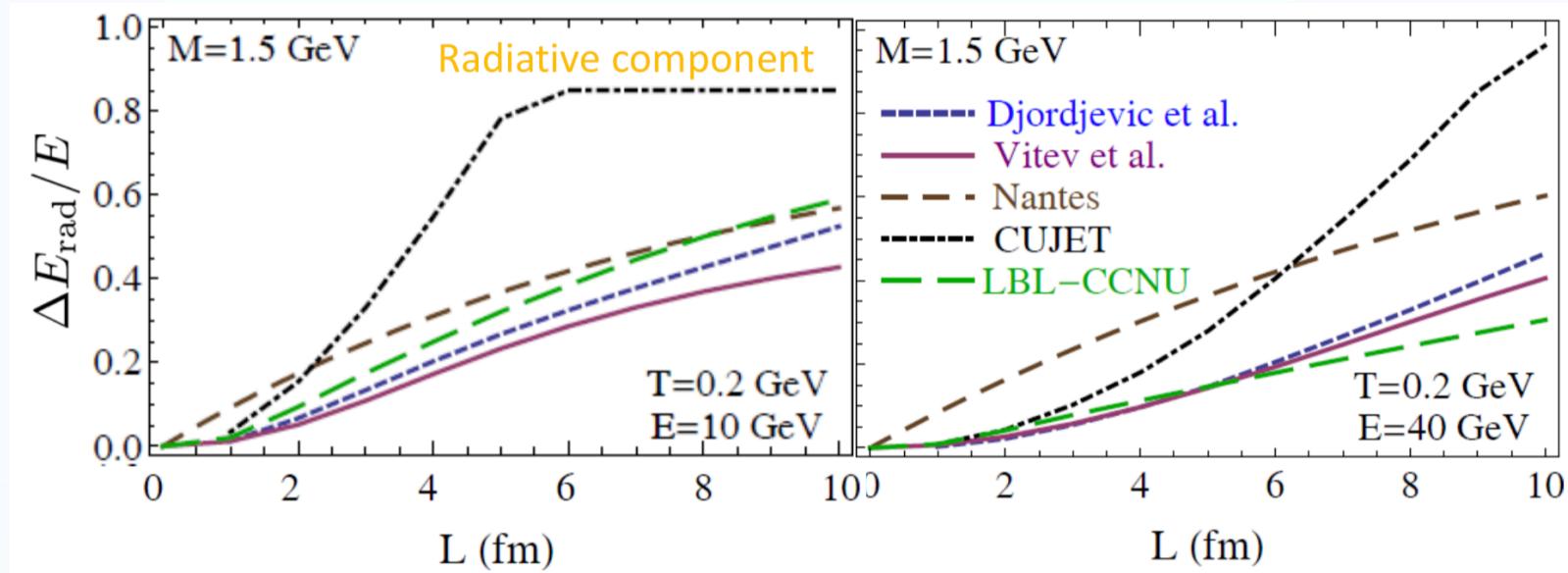
Evolution of energy vs. momentum broadening



- Less divergence in energy evolution, more in momentum broadening
- With similar amount of energy loss (R_{AA}), radiative process reduces momentum broadening, QPM leads to larger broadening than pQCD elastic process
- Need more observables to constrain models, D -hadron correlation, heavy flavor jet shape, etc.

More comparisons between radiative energy loss

R. Rapp et. al., Nucl. Phys. A979 (2018) 21-86 [EMMI-RRTF]



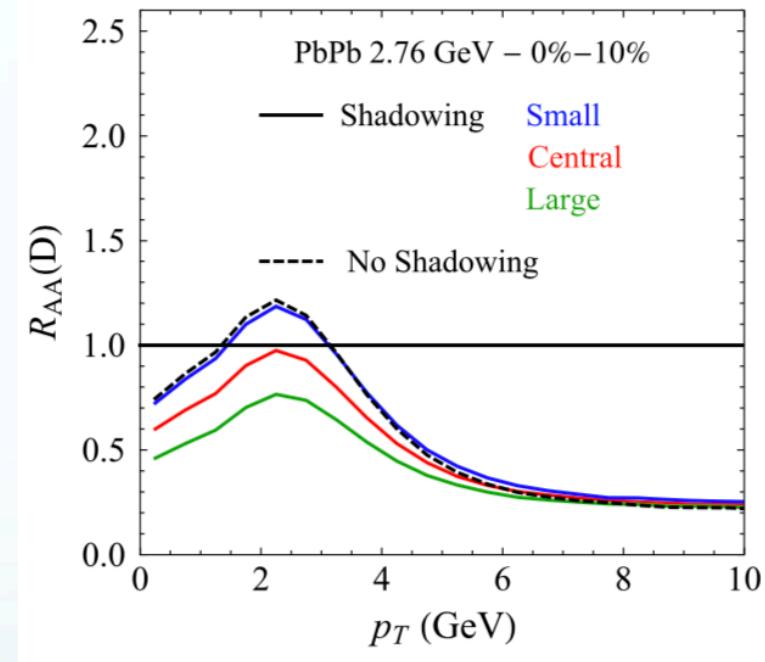
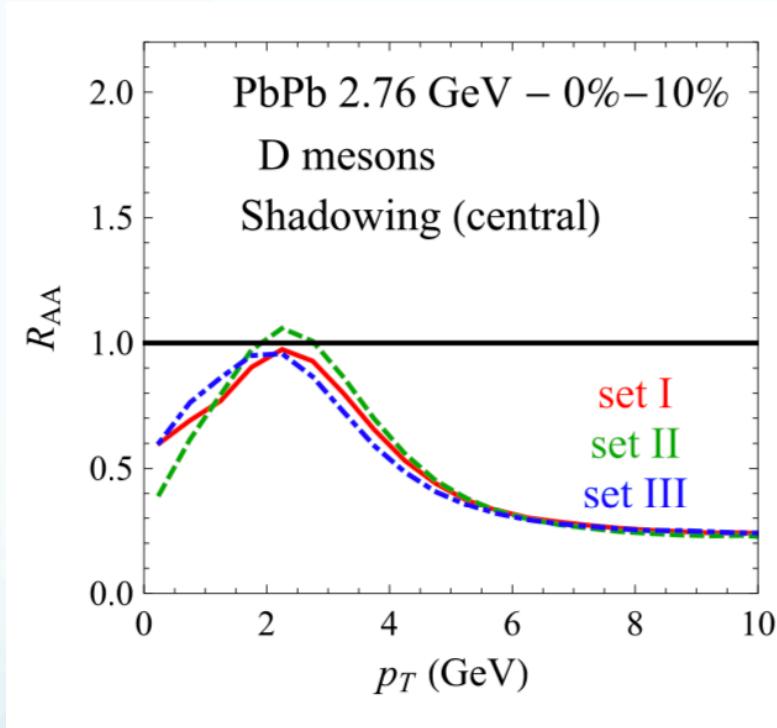
* Djordjevic: DGLV (with dynamical scattering centers); Vitev: SCET; LBL: HT;
Nantes: GB+BDMPS; CUJET: DGLV + magnetic monopole

- HT, SCET and DGLV are consistent
- Different L -dep. with BDMPS
- Additional features with magnetic monopoles, especially at low temperature near T_c

Systematic uncertainties beyond energy loss

R. Rapp et. al., Nucl. Phys. A979 (2018) 21-86 [EMMI-RRTF]

- Initial spectra of heavy quarks

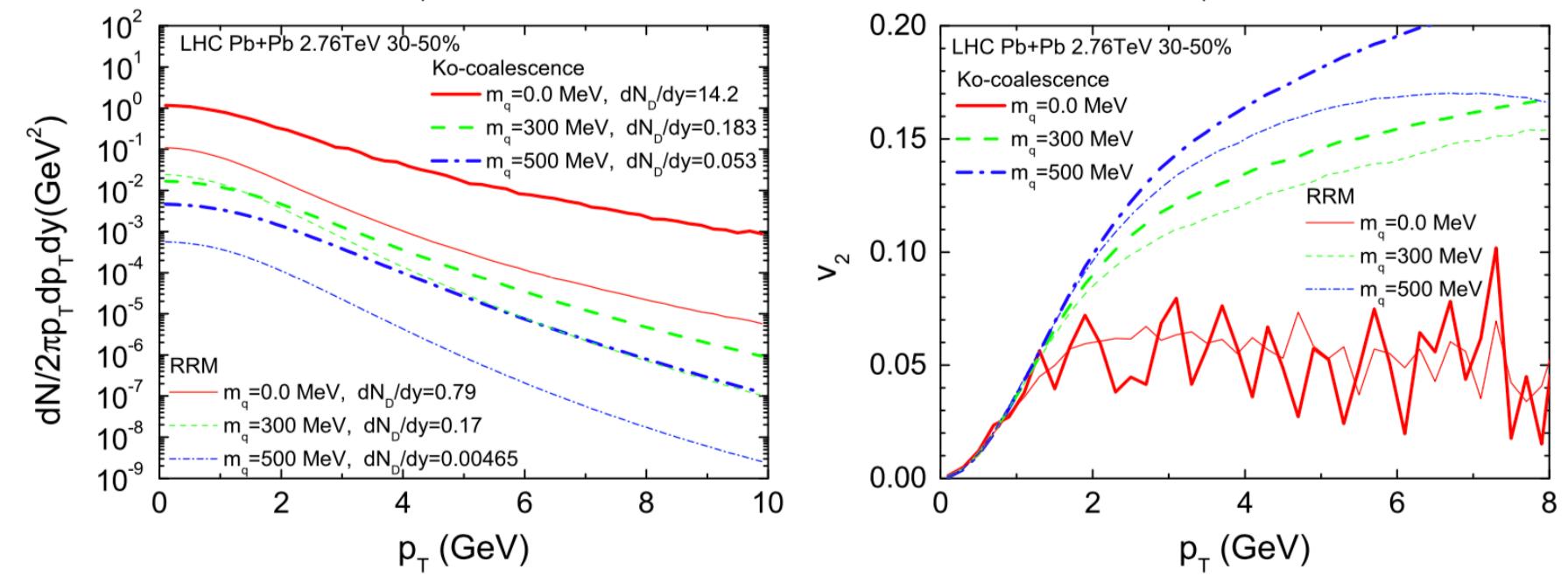


- Different parameter settings in FONNL have little impacts on the D meson R_{AA}

- Different implementations of nuclear shadowing introduce up to a factor of 2 uncertainty at low p_T , negligible above 6 GeV

Systematic uncertainties beyond energy loss

- Hadronization (instantaneous vs. resonant recombination)

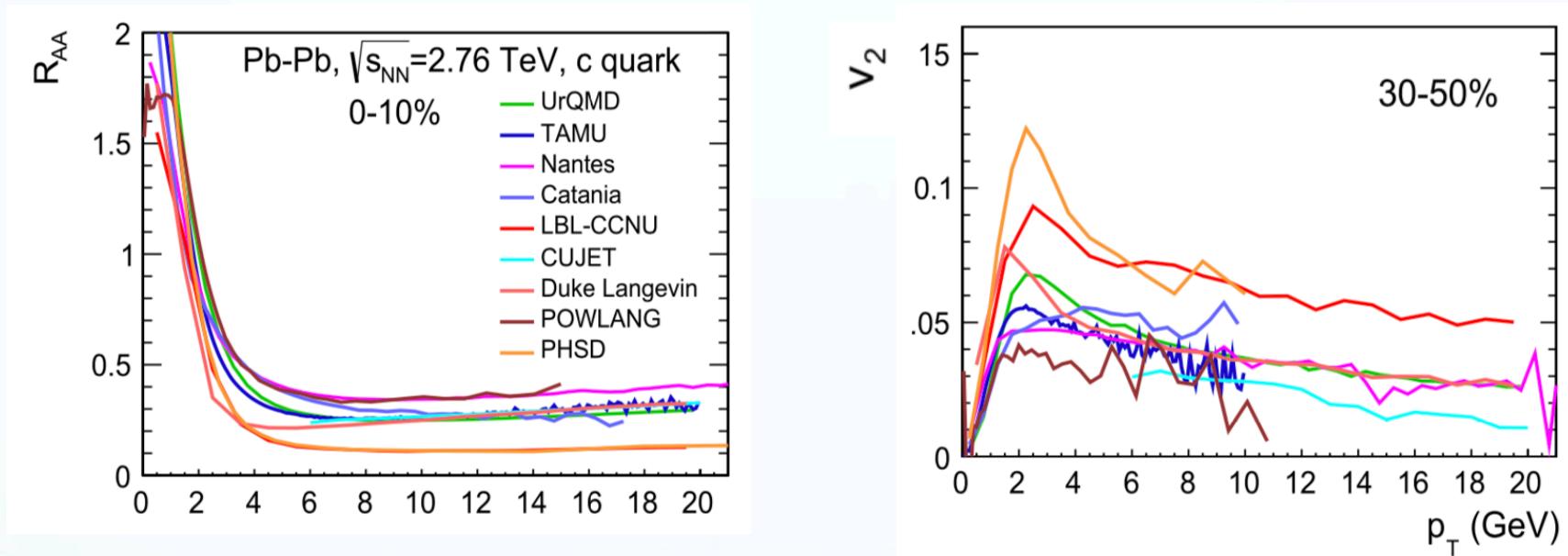


- Resonant recomb. gives smaller and softer D spectra than instantaneous recomb. (thermal mass dependent)

- Larger mass (500 vs. 300 MeV) of light thermal partons gives over 20% larger $D v_2$.
- Instantaneous gives over 10% larger v_2 (for $m_q = 300$ MeV)

Systematic uncertainties beyond energy loss

- The bulk medium



- Same HQ-medium interaction (5^*p QCD σ) in different media -> a factor of over 2 difference in charm R_{AA} and v_2
- Unconstrained medium (by soft hadron spectra) should no longer be used
- Can heavy quarks probe medium properties that cannot be constrained by soft hadron spectra?

Probing nuclear matter with heavy quarks

Can heavy quark probe medium history?

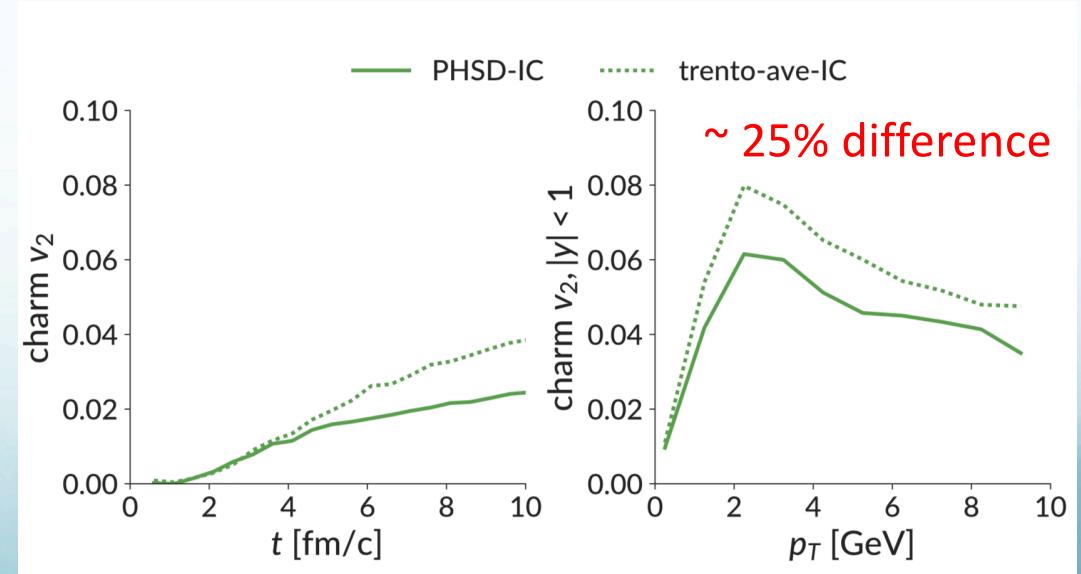
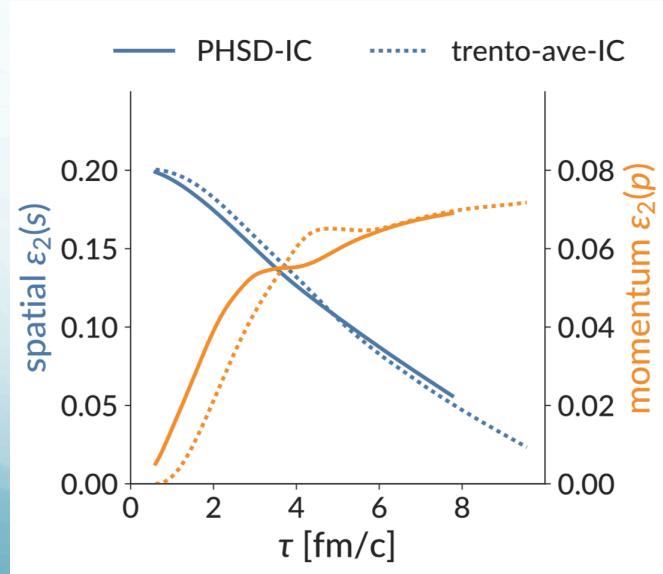
Yes! Y. Xu et. al., Phys. Rev. C99 (2019) 014902 [Duke-Frankfurt]

DFNCC (Duke-Frankfurt-Nantes-Catania-CCNU)

Different initial condition of the bulk (PHSD vs. Trento), same hydrodynamic model and heavy quark transport model

Similar ε_2 and v_2 of the bulk

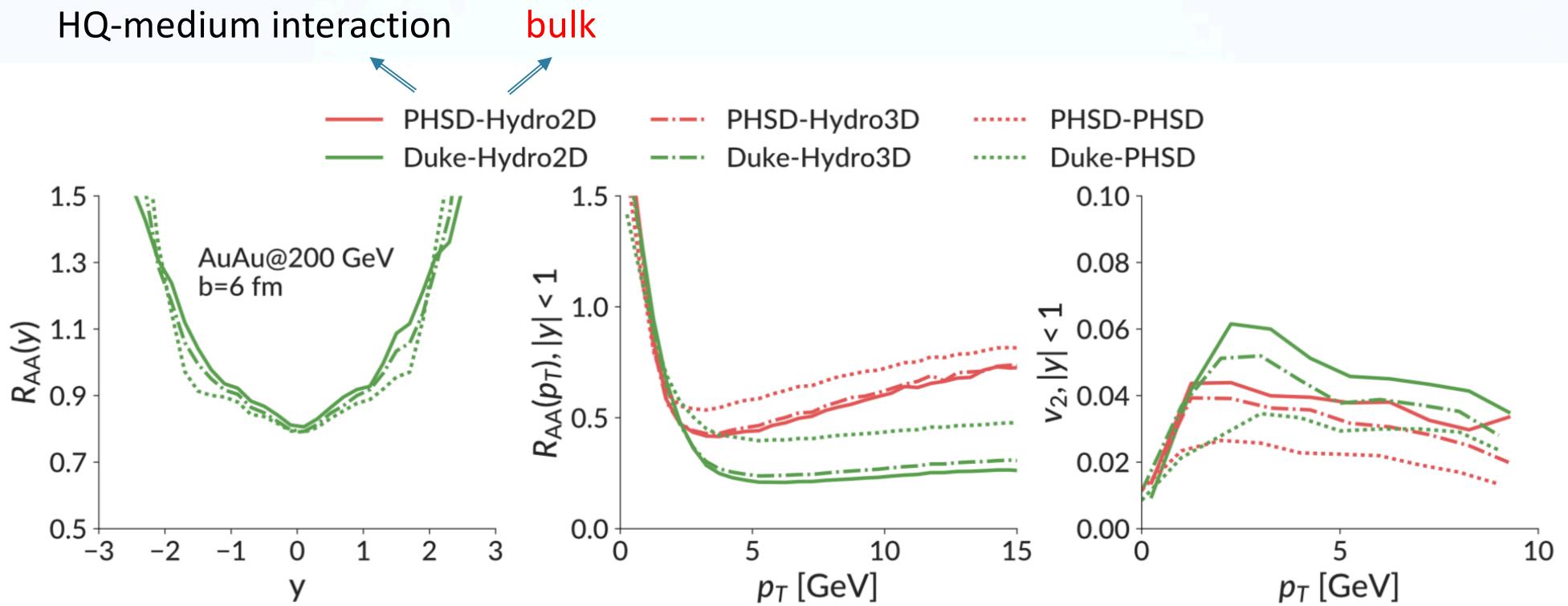
Different $c v_2$: probe different bulk history



Additional systematic uncertainties from bulk

HQ-medium interaction

bulk

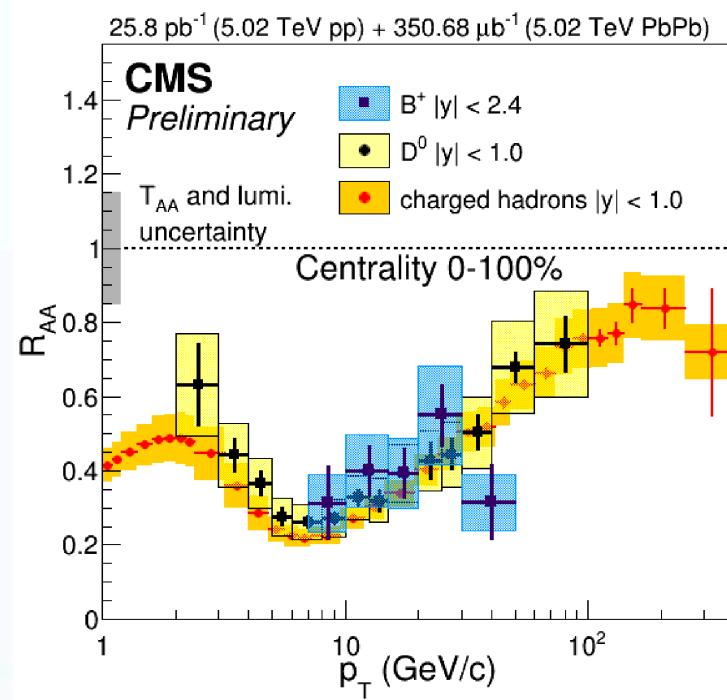


Within each HQ-interaction (same color):

- PHSD medium gives twice charm R_{AA} compared to hydro medium (at large p_T), and smaller v_2 by over 30%
- 2D hydro gives similar charm R_{AA} compared to 3D hydro, but 15% larger v_2 .

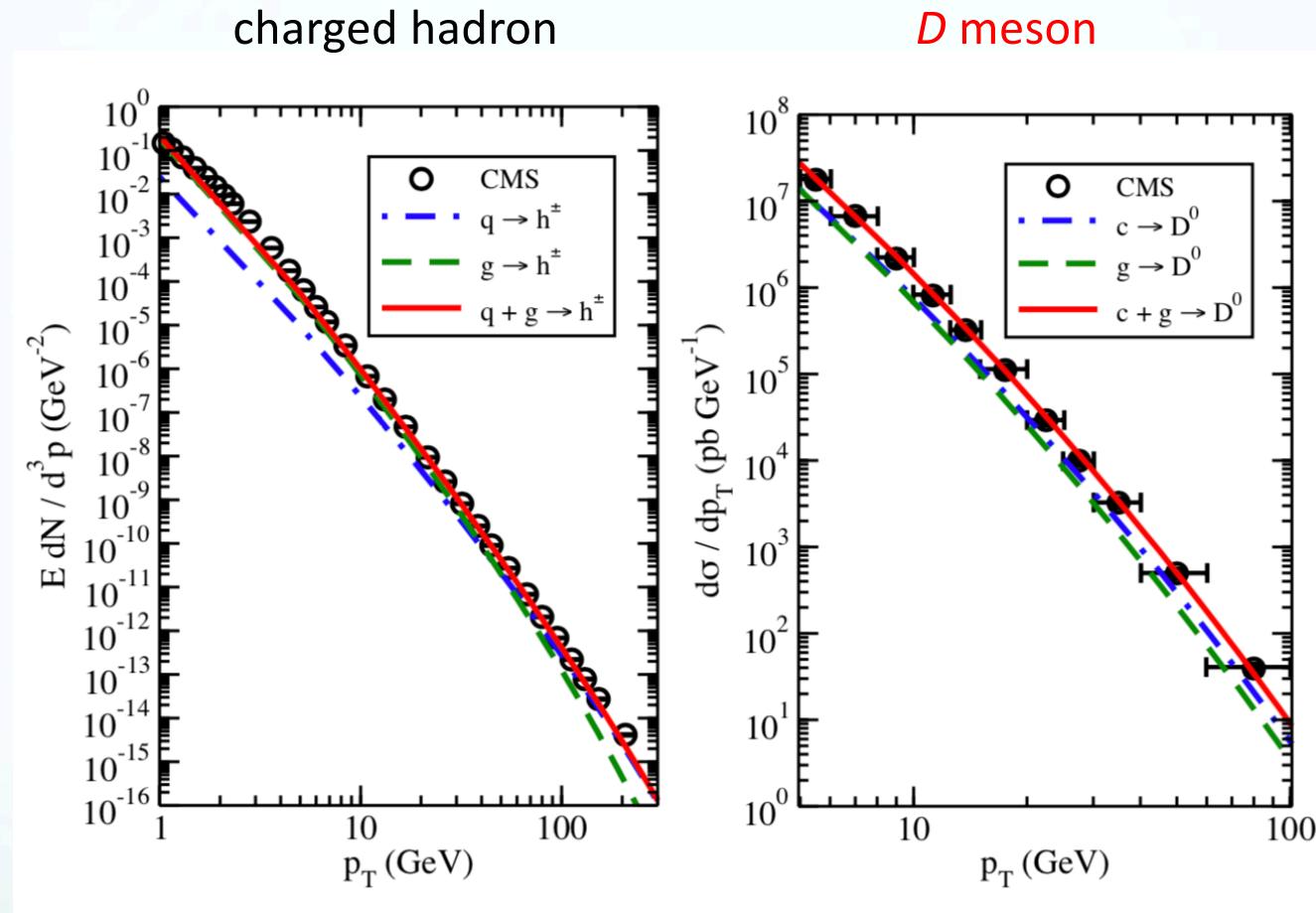
Flavor puzzle of jet quenching

W.-J. Xing, S. Cao, G.-Y. Qin and H. Xing, arXiv:1906.00413



- Flavor hierarchy puzzle: similar R_{AA} between heavy and light flavor hadrons above 6-8 GeV – is $\Delta E_g > \Delta E_q > \Delta E_c > \Delta E_b$ still right?
- Contribution from g fragmentation to D has rarely been studied
- A complete calculation of heavy & light hadron R_{AA} with coll. & rad. energy loss using realistic hydro is still missing

Gluon contribution to light vs. D yields in pp

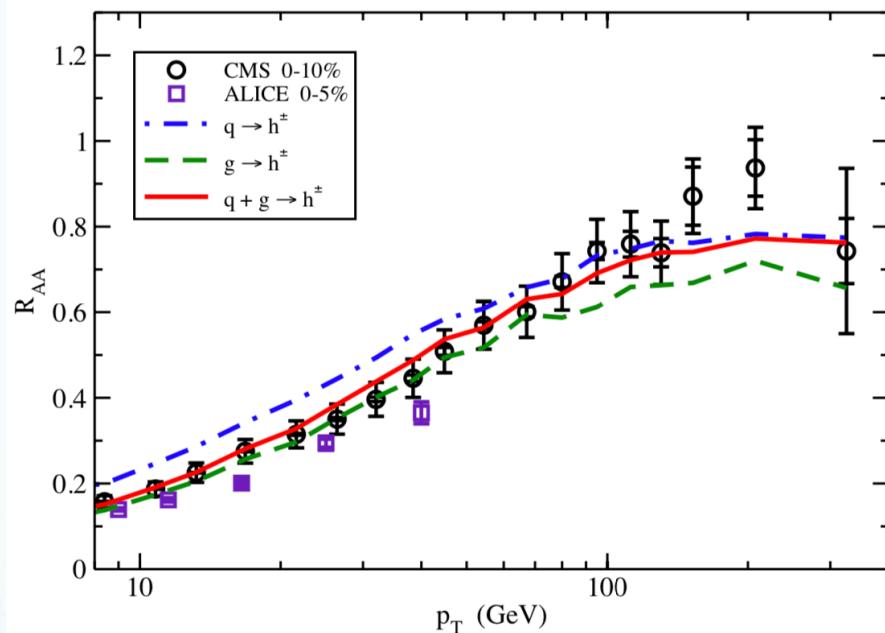


Within NLO initial production + fragmentation framework:

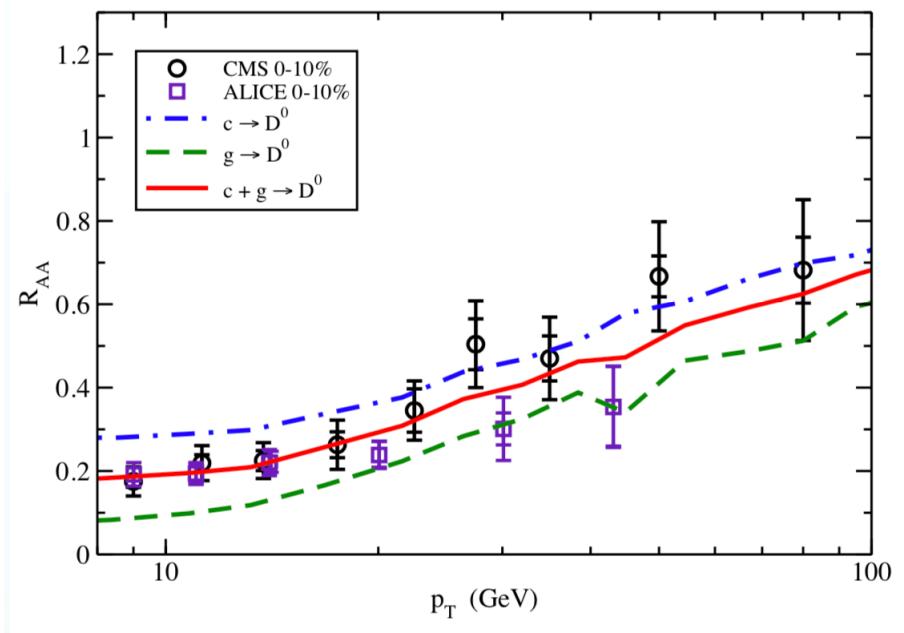
- g fragmentation contribution dominates charged hadron production up to only ~ 50 GeV;
- g fragmentation contributes to over 40% D yield up to 100 GeV.

Gluon contribution to light hadron vs. $D R_{AA}$

charged hadron



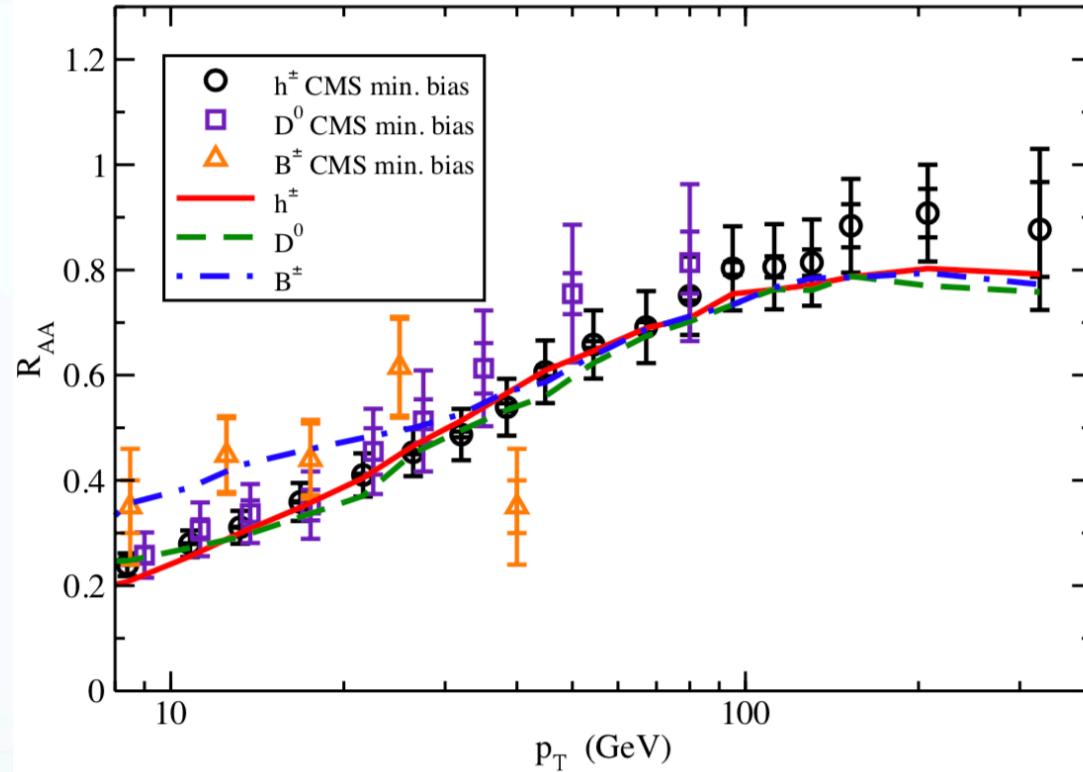
D meson



Within NLO production framework + LBT (linear Boltzmann transport) parton-medium interaction:

- g -initiated h & $D R_{AA} < q$ -initiated h & $D R_{AA} \Rightarrow \Delta E_g > \Delta E_q > \Delta E_c$ still holds
- Although $R_{AA} (c \rightarrow D) > R_{AA} (q \rightarrow h)$, $R_{AA} (g \rightarrow D) < R_{AA} (g \rightarrow h)$ due to different fragmentation functions $\Rightarrow R_{AA} (h) \approx R_{AA} (D)$

Solution to flavor puzzle of jet quenching



- A simultaneous description of charged hadron, D and B meson R_{AA} 's over the widest p_T range (8-300 GeV) in literature
- Predict R_{AA} separation between B and charged hadron / D at not-very-high p_T but similar value above 40 GeV – can be tested by future precision measurement

Summary

- Discussed sources of different uncertainties in theoretical calculations of heavy quark observables
- Reduced the uncertainty in extracted drag coefficient from a factor of 5 (at high p_T) to 2 (due to different energy loss methods) after eliminating medium and hadronization effects
- Quantified uncertainties from other sources: initial spectra – negligible at high p_T ; hadronization – up to 20%; bulk medium – a factor of over 2
- Investigated contribution from gluon fragmentation to hadron production – important to simultaneous description of heavy and light flavor R_{AA} 's (flavor puzzle of jet quenching solved)

Thank you!

